

## EXECUTIVE SUMMARY

Hydrogen is an energy carrier with the potential to open the door to a wide range of new energy technologies and policy options. Fuel cells powered by hydrogen or other fuels can achieve high efficiencies and have a variety of possible uses in mobile and stationary applications. In the right circumstances hydrogen and fuel cells technologies could make major contributions to the key policy objectives of energy security and mitigation of carbon dioxide (CO<sub>2</sub>) emissions, especially in the transportation sector. Recent advances in hydrogen and fuel cell research and development have tremendously increased the interest of the international community in these technologies which have the potential to create paradigm shifts in transport and distributed power generation. There are approximately 400 demonstration projects currently in progress world wide.

Of the many technology options, the possibility of hydrogen powered fuel cell vehicles is perhaps the most far reaching. It has attracted widest interest and unprecedented research investment by Governments and private firms in the automobile and energy sectors. Replacing petrol used in vehicles could, obviously, have major advantages for energy security and climate change mitigation. And fuel cell powered vehicles could be a new, attractive market with benefits for the global economy. Hydrogen can also reduce CO<sub>2</sub> emissions when it is produced from renewables and nuclear energy. If the source of the hydrogen is natural gas or coal then the capture and storage of CO<sub>2</sub> is essential to achieve emission savings. In all cases, hydrogen fuel cell vehicles reduce local environmental pollution, as the only effluent is water vapour.

Governments, private companies, and experts have different views and expectations regarding the prospects for hydrogen and fuel cells. There is a complex array of technologies and processes for hydrogen production, storage, transportation, distribution, different types of fuel cells, and other end use technologies. There is also a range of competing technologies with the potential to meet, at least in part, some of the same policy objectives. These include biofuels, and various forms of electric or hybrid vehicles. This study has tried to take a realistic view of the potential for hydrogen taking account, also, of the potential of these other technologies.

The study was conceived in the framework of the IEA Hydrogen Co-ordination Group, established in 2003, and utilises the IEA's Energy Technology Perspectives model. The analysis draws on the IEA's extensive international energy technology network and takes account of the results of workshops involving national and private sector experts in the field, including key industry associations.

While recent technology advances have been impressive, most hydrogen technologies are currently substantially more costly than their conventional counterparts. And a transition to hydrogen would require infrastructure investment in the range of several hundred billion to a few trillion dollars, over several decades, depending on timing and assumptions as to the investment that would eventually have been needed in the alternative system.

Nevertheless, hydrogen and fuel cells may have a major role in the future energy market if current targets for reducing technology costs can be met and if governments give high priorities to reducing CO<sub>2</sub> emissions, to improved energy security and to research and development efforts. In the next few decades, hydrogen production costs need to be reduced 3 to 10 fold, depending on the technology used, and fuel cell costs by 10 to 50 fold. Substantial improvements are also needed to overcome key technology issues concerning fuel cells and hydrogen on-board storage for fuel cell vehicles. Governments would need to adopt policies that incentivise CO<sub>2</sub> emission savings by giving a value to the emissions avoided. They would also need to adopt policies to diversify the energy supply. However, policies for enhanced security on their own would not be

sufficient. In the absence of CO<sub>2</sub> policies, there are other technologies and fuels (such as coal) that could diversify energy supply at less cost. In any case, new technologies are needed to support CO<sub>2</sub> and energy security policies.

The analysis suggests that if these most favourable conditions are met then 30% of the global stock of vehicles could be powered by hydrogen fuel cells by 2050 – about 700 million vehicles. The oil consumption of the same number of petrol engine vehicles would have been some 15 million barrels per day, equivalent to around 13% of global oil demand (or 5% of the global primary energy demand) in the reference scenario at the time. It is important to recognise, however, that, in the absence of hydrogen, other low carbon technologies such as biofuels and synfuels from coal and gas might also have saved much of this oil in the policy environment assumed. Because the efficiency of the hydrogen fuel cell vehicles (*e.g.* using Proton Exchange Membrane fuel cells) is more than twice that of conventional engines the total energy content of hydrogen used would be much less than this – less than 3% of the global primary energy demand.

If hydrogen used for energy applications is added to hydrogen used in refinery and chemical industry then, in this most favourable scenario, the total amount of hydrogen used in 2050 would be some 180 million tonnes of hydrogen per year, equivalent to more than a 4-fold increase in comparison with today's hydrogen use.

However, hydrogen and fuel cell vehicles will only play a significant role under these favourable assumptions. If less optimistic assumptions are considered for technology development and policy measures, hydrogen and fuel cell vehicles are unlikely to reach the critical mass that is needed for mass market uptake. Competing fuels with lower infrastructure costs, such as biofuels and synthetic fuels derived from coal and gas, would play a larger part.

Stationary fuel cells are a more robust technology option that is much less sensitive to energy policies and competing technology options. Stationary solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC) – mostly fuelled by natural gas – can contribute to meeting the demand for distributed combined heat and power with some 200-300 Gigawatts, equal to 2-3% of global generating capacity in 2050. Currently, private investment in stationary fuel cells and installed capacity is continuously growing.

This analysis does not take account of the possibility of major breakthroughs in some high-risk/high-potential technologies that are presently in their infancy. These include new concepts and materials for fuel cells, and on-board solid hydrogen storage and production technologies, such as photo-electrolysis, biological production, and water splitting by nuclear and solar heat. These technologies have the potential to make a tremendous impact on the future of hydrogen and fuel cells and the whole energy system. Of course, breakthroughs are also possible in competing technologies, such as electric vehicle batteries.

## Conclusions and recommendations

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Uncertainty indeed remains as to the mix of technologies that will play the largest parts in meeting the challenges of global warming, energy security and economic efficiency in the longer term. It is essential, therefore to continue to develop a broad portfolio. The technologies associated with hydrogen and with fuel cells are amongst those with the greatest potential, in particular, for the transport sector. Consistent with this portfolio approach, governments should, therefore, continue to sustain research, development, and demonstration programmes for hydrogen and fuel cells, with a focus on:

- Cost effective production of hydrogen that meets environmental and quality standards.
- New materials and concepts to reduce the costs and increase the durability of fuel cells.
- Reliable and economic systems for hydrogen on-board storage in fuel cell vehicles.
- Concepts and technologies for reducing the cost and the energy consumption of hydrogen transportation and distribution.
- Basic science research in areas such as photo-electrolysis, high temperature water splitting, biological production of hydrogen, new materials for hydrogen storage and fuel cells, and nanotechnologies. For this purpose it is important to retain the links between the basic and applied science communities.

Deployment of hydrogen infrastructure at this point would be premature, as some of the key technical issues that are still being worked on – such as fuel cell operating conditions and hydrogen on-board storage – may have a considerable impact on the choice of technologies for hydrogen production, distribution, and refuelling. However, continued international co-operation on R&D, infrastructure concepts, and harmonisation of codes and standards remains vital in the light of the global nature of the transport industry.

As natural gas and coal are likely to remain the lowest-cost sources of hydrogen for many years to come, large-scale CO<sub>2</sub> capture and storage, already of the highest importance to mitigate emission in the power sector, is also a vital step towards the wider use of hydrogen.

In the coming years, full use should be taken of niche opportunities to deploy fuel cell vehicles, for instance in public service fleets (buses, delivery vans) where the economics are more attractive than for private cars, and in situations where low-cost hydrogen is available. Such programmes can start the process of cost reduction through larger scale manufacture, can broaden operating experience, and can begin to familiarise the public with these technologies.